New developments in instrumentation at the W. M. Keck Observatory

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ABSTRACT

The W. M. Keck Observatory continues to develop new capabilities in support of our science driven strategic plan which emphasizes leadership in key areas of observational astronomy. This leadership is a key component of the scientific productivity of our observing community and depends on our ability to develop new instrumentation, upgrades to existing instrumentation, and upgrades to supporting infrastructure at the observatory. In this paper we describe the as measured performance of projects completed in 2014 and the expected performance of projects currently in the development or construction phases. Projects reaching completion in 2014 include a near-IR tip/tilt sensor for the Keck I adaptive optics system, a new center launch system for the Keck II laser guide star facility, and NIRES, a near-IR Echelle spectrograph for the Keck II telescope. Projects in development include a new seeing limited integral field spectrograph for the visible wavelength range called the Keck Cosmic Web Imager, a deployable tertiary mirror for the Keck I telescope, upgrades to the spectrograph detector and the imager of the OSIRIS instrument, and an upgrade to the telescope control systems on both Keck telescopes.

Keywords: Adaptive Optics, Infrared, Instrumentation, Integral Field, Laser Guide Star, Spectrograph, Targets of Opportunity, Telescope Control

1. INTRODUCTION

In March of 2013 the W. M. Keck Observatory (WMKO) celebrated the 20th anniversary of the first science operations with the Keck I telescope. The first science operations on the Keck II telescope followed in 1996, and since that time the Observatory has become one of the premier facilities for ground-based optical and infrared (O/IR) astronomy in the United States, and is ranked as the most scientifically productive ground-based observatory in the world. In 2012 and 2013, a total of 632 refereed publications were published based on Keck data. Studies of the citation frequency show that WMKO has the highest total scientific impact per telescope of all ground-based O/IR observatories worldwide[1]. In addition, WMKO is an important asset to our observing community in the training of students and post-doctoral researchers. 287 PhD theses were produced using Keck data through 2013 and the list of astronomers who made use of WMKO observing data for their theses includes many of the emerging and mid-career leaders in U.S. astronomy.

Access to science observing time with the Keck telescopes is determined by time allocation committees (TACs) representing the institutions with direct interests in the Observatory: the California Institute of Technology (Caltech) and the University of California (UC), NASA and the University of Hawaii (UH). The WMKO observing community has expanded to include Yale University, Swinburne University of Technology, and the Australian National University (ANU). Access by Swinburne is through a share of the time allocated to Caltech. Yale has access through Caltech time and also, with ANU, access to time (allocated through their own TACs) made available by the contribution of observing nights from Caltech, UC, and UH through an arrangement similar to the one that made time available in the past to the broader U.S. community through the National Optical Astronomy Observatory TAC as part of WMKO's participation in the Telescope System Instrumentation Program (TSIP).

The development program at WMKO includes not only the development of new instrumentation, but also the development of major upgrades to existing instrumentation, and the development of enhancements to and replacements of our infrastructure such as the current project to upgrade the control systems on both telescopes. Such efforts are a

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natural consequence of the Observatory's age which requires replacing obsolete equipment and systems with more modern ones that offer benefits in performance as well as maintainability.

The primary goal of our development program is to provide the best possible tools for our observing community and to ensure that our facility is ready to observe every night. The prominence of WMKO in astronomy results from the synergy between the skill and passion of our observers in their fields of astronomical science, and the dedication of the Observatory and its collaborators to the development of state of the art instrumentation and systems.

2. NEW DEVELOPMENTS IN INSTRUMENTATION

2.1 Adaptive Optics

The first science operations with laser guide star (LGS) adaptive optics (AO) began in 2004 on the Keck II telescope[2].Since that time LGS AO has been commissioned for science operations on the Keck I telescope[3] and LGS AO has grown to be a significant part of the WMKO community's requested observing time, accounting for over 140 nights of the nominal 700 nights per year available for observing on the two telescopes. Publications based on AO observations have grown in number as well, with a total of 515 refereed science papers published as of April 2014 using Keck AO observations, with 193 of these based on LGS AO observations. The increasing acceptance of AO by our observing community demonstrates the impact of WMKO's commitment to increasing the capabilities of our AO system and AO instrumentation, and input from our community on their science needs motivates us to continue to develop our AO capabilities. In 2014 we are nearing completion of two upgrades to our AO systems and we are in the detailed design phase of a third upgrade. All of these upgrades also pave the way for our plans to design and build our next generation adaptive optics system (NGAO)[4].

2.1.1 Near-IR Tip/Tilt Sensing for the Keck I AO System

LGS AO systems rely on a natural guide star (NGS) for the sensing of atmospheric tip-tilt. In the Keck AO systems tip-tilt sensing is performed using visible wavelengths with a faint magnitude limit of R = 19 up to 60" off axis from the science target. The result is a limit on sky coverage due to the relatively low availability of suitable tip-tilt stars. Implementing a near-IR tip-tilt sensor allows a greater fraction of the sky to be accessed because of the increased brightness of the stars in the infrared, and the increased concentration of the star light because the AO system can provide partial correction of the star image.

With support from a National Science Foundation (NSF) grant we have implemented a near-IR tip-tilt sensor on the Keck I AO system. The Keck I system was chosen since it has a higher power center launched laser and hence higher Strehl performance. A tip-tilt camera (Figure 1) using a Hawaii-2RG detector has been installed in the Keck I AO system along with an optical pick-off that allows the sensor to operate in either the Ks or H bands while allowing observing in the other near-IR bands with the OSIRIS instrument. The first night of on-sky testing demonstrated closed loop operation using the near-IR tip-tilt sensor with NGS too faint to use in the visible wavelengths, and an improved H-band Strehl ratio. Further on-sky testing is scheduled for the fall of 2014 and further details of our near-IR tip-tilt sensor design and testing may be found in the paper by Wizinowich et al.[5] in the proceedings of this conference.

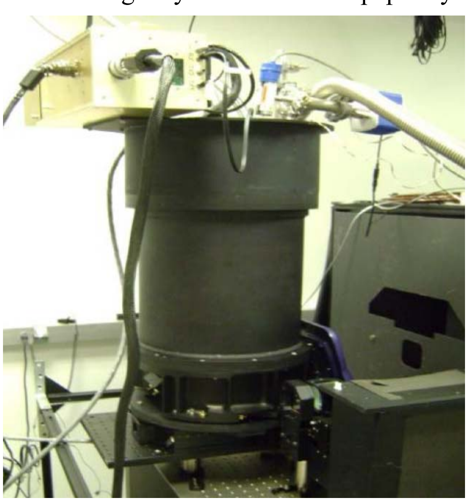


Figure 1: Near-IR tip-tilt camera

Our planned NGAO system will incorporate three near-IR tip-tilt sensors and the successful development of this first near-IR tip-tilt sensor provides an important reduction in the level of risk for the NGAO tip-tilt sensors

2.1.2 LGS Facility Upgrades for the Keck II AO System

Two LGS facility upgrades are underway for the Keck II AO system, a center launch facility for the Keck II laser, and a new laser for the Keck II AO system.

The center launch facility is being developed with support from the NSF Major Research Instrumentation (MRI) program. This system replaces the side launch facility that is original to the Keck II LGS facility. Center projection has the well-known benefit of reducing perspective elongation of the laser spot images in the atmospheric sodium layer. The system uses a 50 cm f/1.4 reflector telescope to project the laser beam and a free-space beam transport system to bring the laser output to the launch telescope from the laser power amplifier system located on the telescope elevation ring. The beam transport system implements a number of lessons learned from the implementation of the Keck I LGS facility's beam transport system and the new beam transport system and launch telescope co-exist with the side launch facility to facilitate engineering tests of the new center launch facility without disrupting Keck II AO observing. The center launch facility was installed on Keck II in January 2014 and we expect to begin shared risk observing with the facility and the existing Keck II dye laser in August of 2014.

A new laser[6] for the Keck II AO system is being developed in collaboration with the European Southern Observatory (ESO), and the Thirty Meter Telescope project. The new laser is based on frequency doubling of 1178 nm light from a 35 W Raman fiber amplifier (RFA) laser pump source and will generate 20 W of optical power at the sodium D2a line, and 2 W of power at the sodium D2b line. This two line operation allows "re-pumping" of the sodium atoms from the lower ground state into higher states renewing photon interaction and significantly increasing the brightness of the LGS image[7]. The new laser is currently in the in the production phase and delivery is expected later in the summer of 2014. The new laser's head assembly containing the RFA and resonant frequency doubler will be mounted on the Keck II telescope's elevation ring in the existing enclosure used for the power amplifier and beam conditioning optics of the existing dye laser which will be decommissioned. The layout of this enclosure allows for the addition of two more laser heads for our planned NGAO system. The pump sources for the RFA along with up to three sets of laser electronics, and a cooling system will be mounted on a platform located underneath the Keck II right Nasmyth platform (Figure 2).

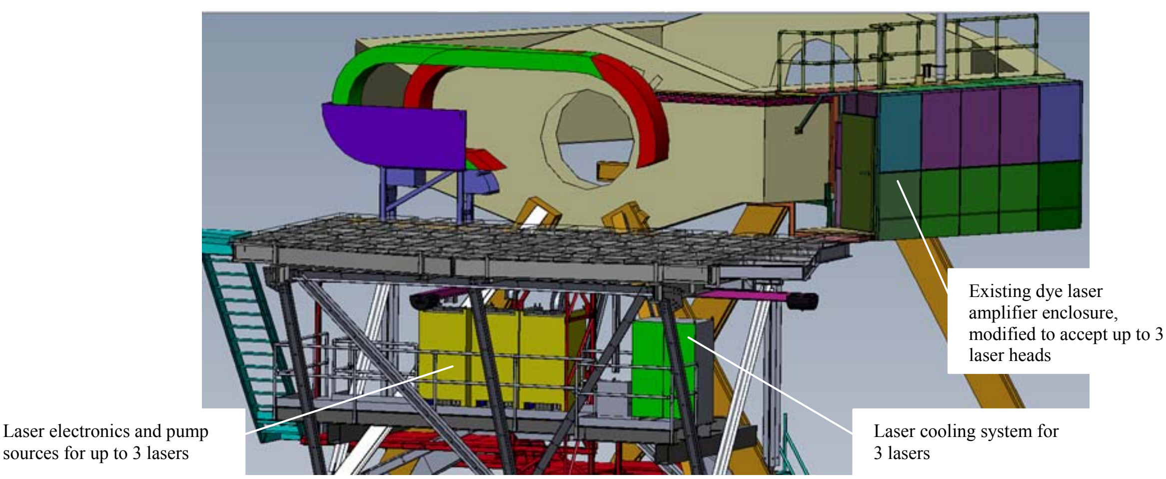


Figure 2: Laser enclosures at the Keck II right Nasmyth position

The design of the new laser platform and the related modifications to the existing dye laser amplifier enclosure on the elevation ring are currently in the detailed design phase. Installation of the new laser is planned for mid-2015. Further details of the Keck II LGS facility upgrades, as well as an overview of the Keck I LGS facility, and discussion of the performance of both LGS AO systems may be found elsewhere in these proceedings in the paper by Chin et al.[8].

2.2 NIRES

The Near InfraRed Echellette Spectrometer, NIRES, is the third version of the instrument design known as "TripleSpec"[8]. The other two versions are in operation at Palomar Observatory and the Apache Point Observatory. NIRES has been constructed at Caltech under the leadership of Keith Matthews. Since NIRES is the third in the series it has been able to take advantage of improvements in IR detectors and utilizes a Hawaii-2RG detector for the spectrograph while the other two versions use a Hawaii-2. A Hawaii-1is used in NIRES for the slit viewing camera's detector, the same as the other two versions of TripleSpec.

The cross dispersed design enables NIRES to take spectra in five orders simultaneously, covering the wavelength range of 1.0 to 2.45 µm at R ~2,700. A fixed 0.55" slit is used and the slit viewing camera has a 2.1' x 2.1' field of view with a fixed Ks pass band. Figure 3 shows NIRES in the lab at Caltech. Astronomical Research Cameras (ARC) Gen III readout systems are used for the spectrograph and slit viewing detectors. The instrument is equipped with active flexure correction for the spectrograph provided by a piezoelectric actuator mount on one of the fold mirrors in the spectrograph's optical path. Liquid nitrogen is used to cool the instrument.

NIRES will be mounted on the Keck II telescope at a "bent Cassegrain" port. This port is located on the telescope's elevation ring 40 degrees clockwise from the right Nasmyth focus. The bent Cassegrain port is fed by the tertiary mirror, and is equipped with an off-axis guide camera. The instrument and the guide camera are mounted on a rotator to compensate for the field rotation of the telescope, and a cooled enclosure is mounted nearby on the elevation ring to house electronics and power supplies.

NIRES is in the final stages of laboratory integration and testing. Delivery to WMKO is expected in the early fall of 2014, with first light occurring approximately 1 month after delivery.

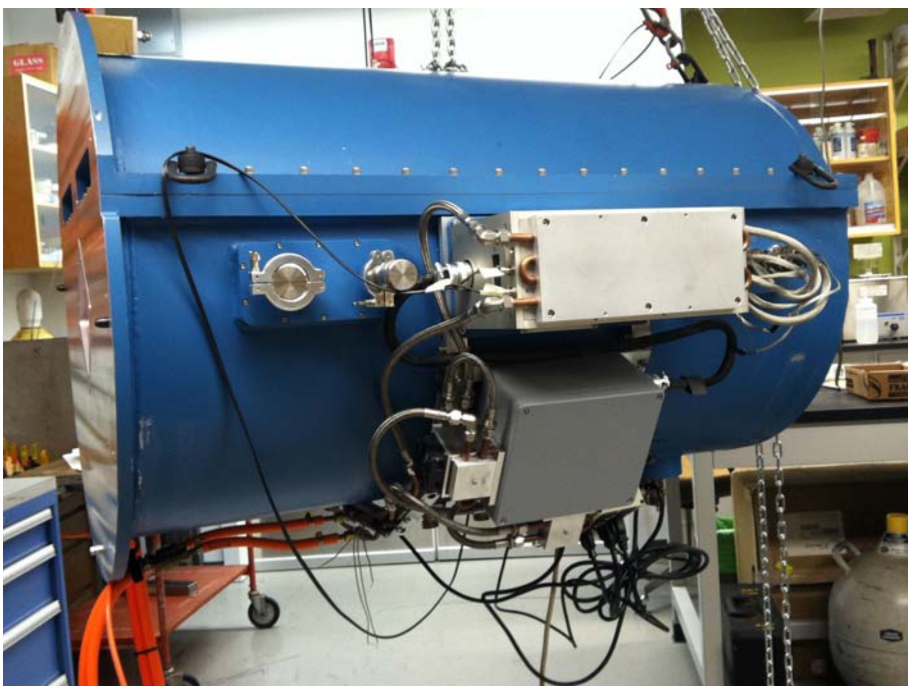
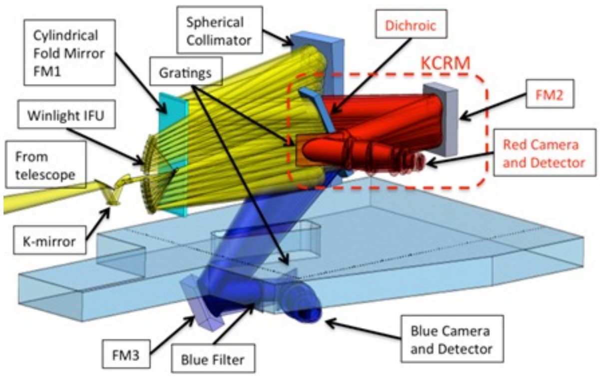


Figure 3: NIRES in the lab at Caltech

2.3 KCWI

KCWI, the Keck Cosmic Web Imager, is an integral field spectrograph for the visible wavelengths being developed for the Keck II telescope. KCWI will provide seeing-limited integral field spectroscopy with moderate to high spectral resolution, high efficiency, and excellent sky subtraction with available nod and shuffle capability. KCWI is a two channel instrument designed for phased implementation with the blue channel covering the wavelength range of 350 to 560 nm, and the red channel covering 530 to 1050 nm. The instrument with the blue channel is currently in the full scale development phase, with delivery to the Observatory planned for mid-2015. The optical layout of KCWI is shown on the left side of Figure 4 and the instrument's key performance parameters are shown in the table on the right side of Figure 4.



Parameter	Value
Field of View	Selectable: 20" x (8.4|16.8| 33.6)"
Spatial Res./Sampling	Selectable: 0.35" x (0.35|0.7|1.4)"
Spectral Resolution	Selectable: 1,000 to 20,000
Bandpass (red & blue)	350 to 1050 nm
Efficiency	>40% (instrument)
3σ Sensitivity in 1 Hour	10^{-7} to 10^{-6} ph/s/cm^2/arcseccond^2/Å
Light Bucket Sensitivity	200 LU in 10 hours
Background Subtraction	0.01% of sky
Plate Scale	0.15" pixel^{-1}

Figure 4: KCWI optical layout and key performance parameters

KCWI will be located at the right Nasmyth focal station of the Keck II telescope, allowing the instrument to operate in fixed gravity with science field rotation compensated by a k-mirror image de-rotator. The instrument is constructed on a large optical bench with the large common optical elements and the red channel of the spectrograph mounted on top of the optical bench. The blue channel of the spectrograph is mounted underneath the optical bench. The light at the Nasmyth focal station passes through an instrument hatch and the windowed k-mirror de-rotator to the integral field unit (IFU) selectable image slicer stack located at the telescope focus. The slicer stack sits on a linear stage that selects between 3 slicer formats and a direct imaging alignment camera. A calibration system with a deployable periscope mechanism directs calibration light onto the image slicer. The three selectable slicer mirror stacks provide 0.35", 0.7" or 1.4" spatial resolution and these allow for a range of spectral resolution from 1,000 to 20,000 depending on the grating. The image slicers are slightly curved to re-image the telescope pupil onto the VPH gratings used in each channel. The light from the IFU pupil array proceeds to a spherical collimator and then to a wavefront-correcting cylindrical mirror (FM1), completing the portion of the optical path common to the red and blue channels. Not shown in Figure 4 is a tracking guider assembly located ahead of the science K-mirror that samples a 3' x 3' field located 3.24' off axis. The tracking guider follows guide stars as they rotate about the optical axis during observations, and allows flexibility in selecting the starting PA of the science field to optimize the science observation while allowing a different starting PA for the guider field. This offers a much larger choice of guide stars, and allows the science path unrestricted access to the full optical passband with a compact and stable K mirror.

The KCWI IFU is being developed by Winlight in France. All of the IFU mirror elements have been fabricated, and assembly and polishing of the first slicer scale and the pupil mirror array is in progress. Delivery of the first slicer scale and the pupil mirror array is expected in the fourth calendar quarter of this year. The second and third slicer scales will be delivered approximately 2 months later.

The light from FM1 is split into the red and blue bands by a large dichroic beam splitter. The blue passband is reflected through the optical bench to a final fold mirror in the blue spectrograph channel (FM3). The blue channel only instrument substitutes a flat mirror for the dichroic. All of these mirrors have been fabricated and all but two (the Collimator and FM1) have been coated and are ready for mounting.

At the entrance of the spectrograph there is a band pass filter and a set of transmission gratings implemented with volume phase holographic technology. The filter and gratings can be removed and replaced in the light beam by an automated grating and filter exchanger. This mechanism has been completed and is awaiting integration with the instrument. The filter and the first two gratings are on order, the remaining gratings will be ordered after the start of integration and test.

After the filter and grating the dispersed light from the IFU is imaged onto the blue channel's 4K x 4K CCD detector by a 9 element all spherical camera. All of the camera lenses have been fabricated with excellent results. Five of the 9 elements have been anti-reflection coated, also with excellent results, and the last four elements are in the process of being coated. The camera and detector are mounted on an articulation stage that allows positioning of the camera at the optimum angle required to maximize the efficiency of each grating and this stage has been assembled and is undergoing initial testing.

KCWI is designed for sky limited spectroscopy of low surface brightness phenomena, and this requires the instrument to have high throughput and excellent sky subtraction. A significant emphasis has been placed on the optimization of the instrument's reflective coatings, with extensive testing of several enhanced performance protected silver coatings for the IFU, collimator, and FM1. A protected aluminum coating with high reflectivity is used for the flat mirror that substitutes for the dichroic and for the FM3 mirror since these optics are used only for the blue channel. Considerable care has also been taken with the anti-reflection coatings in the spectrograph camera, as well as attention given to controlling stray light in the camera. A nod and shuffle mode[10] is implemented for the spectrograph detectors to allow simultaneous observation of the object and the sky background to ensure the best possible sky subtraction performance. The range of 3σ sensitivities listed in the table in Figure 4 reflect the diversity of KCRM instrument configurations and take into account a broad range of possible sky sampling and subtraction approaches. The "light bucket" sensitivity (200 LU is $\sim10^{-9}$ ph/s/cm^2/arcsecond^2) assumes nod and shuffle observations and treats the entire IFU as a single spectroscopic pixel.

The final parts of KCWI to be built and tested as subsystems before integration of the blue channel only instrument begins are the k-mirror image de-rotator, the main optical bench and enclosure for the instrument, and the instrument's electronics rack. Completion of these subsystems is expected in the fourth calendar quarter of 2014. The current status of the KCWI blue channel design and its construction progress may be found in the paper by Morrissey et al.[11] in the proceedings of this conference.

2.4 K1DM3

Time domain astronomy (TDA) continues to be an area of great interest to the WMKO observing community. The availability of wide field synoptic imaging in the optical wavelengths from facilities such as Pan-STARRS and the Palomar Transient Factory has resulted in a very large increase in the number of new transient sources that require follow-up with large ground-based telescopes in the visible and infrared wavelengths. In addition, long term programs such as the study of the Galactic Center and detection of extra-solar planets using radial velocity measurements require regular and frequent observations, but often do not require entire observing nights. At present the Keck telescopes are configured with a single instrument for each night's observing, with switching between instruments being a rare event (the exception to this is when NIRC2 and OSIRIS shared the Keck II AO system and then switching between them was often done, but OSIRIS is now on Keck I). When transient phenomenon are detected, a rapid follow-up response is desirable, and making the optimum observation from the Keck telescopes is not always possible if the best instrument for follow-up is not configured for that night's observing.

The Keck I telescope is equipped with both Nasmyth and Cassegrain instruments that are each useful in different ways for either transient phenomenon or cadence observing. At present, switching between Cassegrain and Nasmyth instruments can only be done during daytime reconfigurations and requires removing or installing the telescope's tertiary mirror. This makes TDA impractical or less effective than it would be if switching between instruments was a simple procedure.

With funding from an NSF MRI grant, the University of California Observatories (UCO) on the campus of the University of California, Santa Cruz, is collaborating with WMKO in the development of a deployable tertiary mirror for the Keck I telescope, called the "Keck 1 Deployable Tertiary Mirror" or "K1DM3". The K1DM3 is a module based on the design of the existing tertiary mirror module, but employing a smaller mirror to make retraction from the beam practical. The Keck telescopes have a 20' field of view, but the current Nasmyth instruments (AO with OSIRIS on the left Nasmyth, and the HIRES spectrograph on the right Nasmyth) require a much smaller field of view. When the bent Cassegrain ports are equipped with off axis guiders they do require a larger field of view of at least 5' and the K1DM3 mirror has been sized to support a 5' diameter field of view as a compromise between field of view and size, weight, and ensuring that the mirror can be moved to a retracted position without vignetting the telescope primary mirror or the Cassegrain focus.

The K1DM3 module is intended to remain in the telescope all the time, and moves between an in-beam position and a retracted position to allow observation with Nasmyth platform or bent Cassegrain instruments by rotating the mirror around the telescope optical axis, or the Cassegrain instruments by retracting out of the telescope beam allowing the light from the secondary mirror to reach the Cassegrain focus. Figure 5 shows the K1DM3 mirror in the deployed and retracted positions.

The left side of Figure 5 shows the top of the tertiary tower at the bottom of the figure with the drum shaped K1DM3 module inside it. The mirror is in the deployed position, held accurately in place by a kinematic interface. The mirror is supported by a whiffle tree structure providing 6 axial supports and a central lateral support. The mirror is moved into the retracted position as shown on the right side of Figure 5 by a swing arm driven by a linear actuator. The gray nearly cylindrical shape extending from the top of the module drum describes the volume occupied by the light beam coming from the telescope's secondary mirror. The module drum provides two bearings to support the mirror and its kinematic interface and to allow the deployed mirror to rotate about the optical axis to direct light to the two Nasmyth focal stations and the four bent Cassegrain ports.

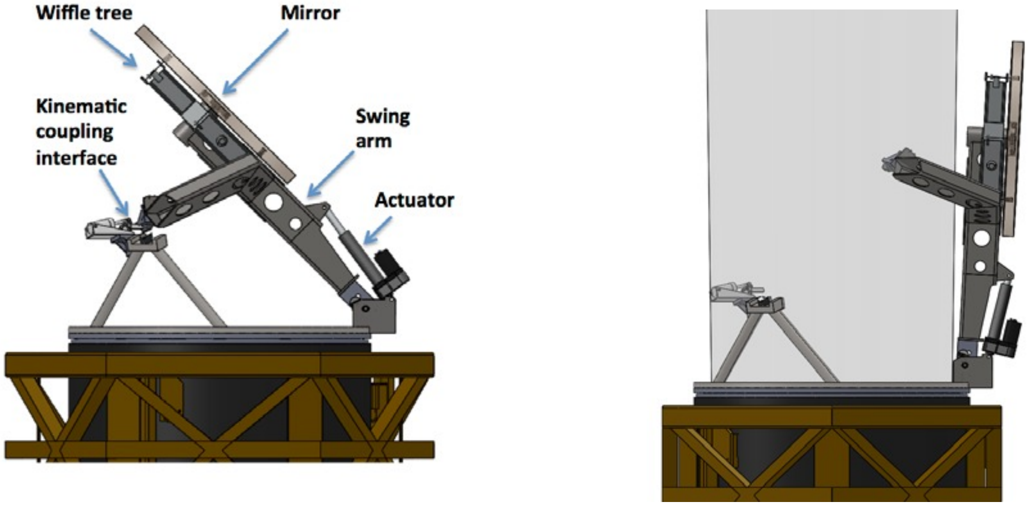


Figure 5: K1DM3 deployed (left) and retracted (right)

The K1DM3 project is in the latter half of the preliminary design phase, with a preliminary design review planned for the early fall of 2014. This will be followed by detailed design and full scale development phases, with delivery to the Observatory in late 2016. A more detailed description of the motivation for the K1DM3 and its current design status is found in these proceedings in the paper by Prochaska et al.[12].

2.5 Upgrades to OSIRIS

The OSIRIS integral field spectrograph (IFS)[13] was commissioned at WMKO in 2005. OSIRIS is a near-IR IFS covering the wavelength range of 1 to 2.4 µm, with spatial sampling scales of 20, 35, 50, and 100 milli-arcseconds (mas). In December 2012 a new spectrograph grating was installed in OSIRIS that has improved its sensitivity by a factor of 1.5 to 2 times depending on wavelength. This upgrade addressed a key limitation of OSIRIS, recognized at commissioning, which was that the grating fell short of its design sensitivity by ~50%. Because OSIRIS uses a very coarsely ruled grating (~28 lines/mm) at a very shallow blaze angle (<6 degrees) it is a challenging grating to manufacture. It took several years before we were able to find a vendor who was willing to make a new grating for OSIRIS. In 2011 we found a vendor, and with funding provided by the Dunlap Institute for Astronomy & Astrophysics at the University of Toronto a new grating was manufactured, tested in the laboratory at the University of Toronto, and installed in OSIRIS[14].

We are now collaborating with the University of California, Los Angeles (UCLA) to develop two additional upgrades to OSIRIS, replacement of the spectrograph's Hawaii-2 detector with a Hawaii-2RG, funded by the NSF ATI program, and replacement of the OSIRIS imager optics and detector with funding from the Gordon and Betty Moore Foundation.

The spectrograph upgrade requires replacing the instrument's detector head assembly with a new detector head designed for the Hawaii-2RG. A Sidecar ASIC based readout system will replace the existing ARC readout system, and eliminates the need for the cryogenic preamplifier boards used with the Hawaii-2. Precise tip-tilt and focus adjustment for the detector is essential to the performance of the IFS, and because adjustment of tip-tilt can require a number of cool down cycles if done manually, we are incorporating a remotely controlled focus stage in the new detector head. This will allow moving the detector through the nominal focus point with sufficient range to allow understanding the direction and magnitude of any tip-tilt adjustment that may be required by observing the PSF of a white light spectrum across the detector as the detector focus stage position is changed. We expect to be able converge on the correct tip-tilt adjustments with only one or two additional cool down cycles. Once the tip-tilt is adjusted the focus stage will be positioned at the correct focus and should not require any further adjustment. The new detector, detector head, and focus stage will be tested cold in the lab at UCLA prior to delivery along with the external interfaces, the detector control computer, and the software. The new detector is expected to improve the sensitivity of OSIRIS by a factor of ~2, and when combined with the improvements realized from the grating replacement the result is a total sensitivity improvement of 3 to 4 times depending on wavelength as shown in Figure 6. The installation of the spectrograph upgrade is planned for August of 2015.

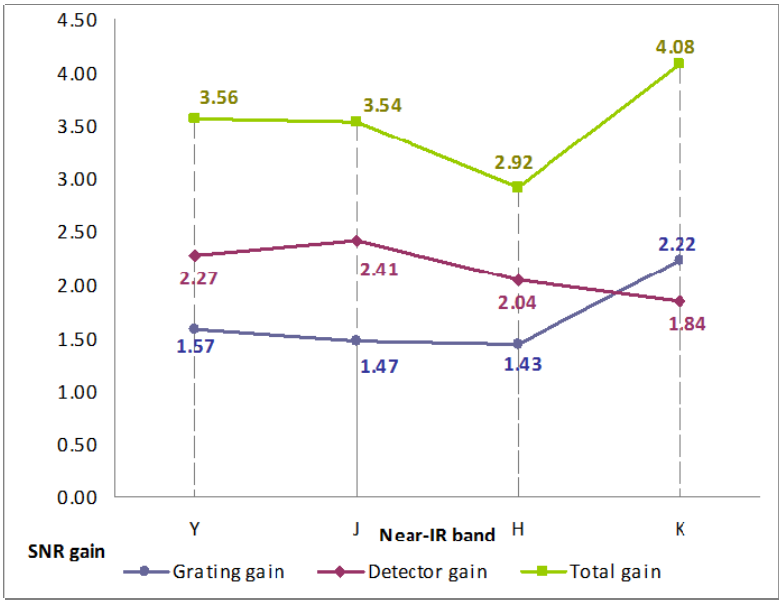


Figure 6: OSIRIS spectrograph sensitivity improvements for the new grating (as measured) and the new detector (predicted)

OSIRIS was moved to the Keck I AO system in 2012. Prior to the move, the 20 mas pixel scale of the imager, and its level of field distortion were not considered significant handicaps because the NIRC2 instrument was easily accessed for well sampled AO imaging with its 10 mas pixel scale if the OSIRIS imager was unsatisfactory. The OSIRIS imager also relies on a Hawaii-1 detector which has relatively high read noise and a slow readout speed with only four readout channels.

The imager upgrade is a much more extensive project than the spectrograph upgrade. The upgrade will completely replace the imager's focal reduction optics, and replace the existing Hawaii-1 detector with a Hawaii-2RG. The existing ARC readout electronics will also be replaced with a Sidecar ASIC based readout system. The imager upgrade will address three key areas that are important for maximizing the science gains from an improved imager. These are a finer pixel scale to take fuller advantage of the angular resolution provided by the AO system, low (< 1%) and stable geometric distortion to support precision astrometry, and improved sensitivity (~2 times greater) by reducing background levels with an efficient cold stop and the higher quantum efficiency and lower noise of the Hawaii-2RG detector. The improvements to the imager will also support our continuing work in the reconstruction of point spread functions for AO observations[15]. Improved PSF knowledge also offers the possibility of improving IFS spectral data extraction. The improved spatial resolution and low distortion while maintaining the present 20" x 20" imager field of view will eliminate the need for image mosaicking when observing fields such as the Galactic Center (GC) to obtain astrometric reference frames for IFS observations. For example, velocity measurements of stars in orbit around the super massive black hole at the GC require precision astrometry. The required precision is obtained by tying the coordinates measured from images of the GC to more precise coordinates obtained from radio observations of maser sources around the GC that are also visible in the infrared. Figure 7 shows a K band image of the 7 maser sources (circled) used to anchor the astrometric reference frames for GC observations. The red outline shows the field of view of the OSIRIS imager, with the dashed lines showing the 9 images that would be required using the smaller field of view provided by the 10 mas pixel scale of NIRC2, the current best source for astrometric images of the GC at WMKO.

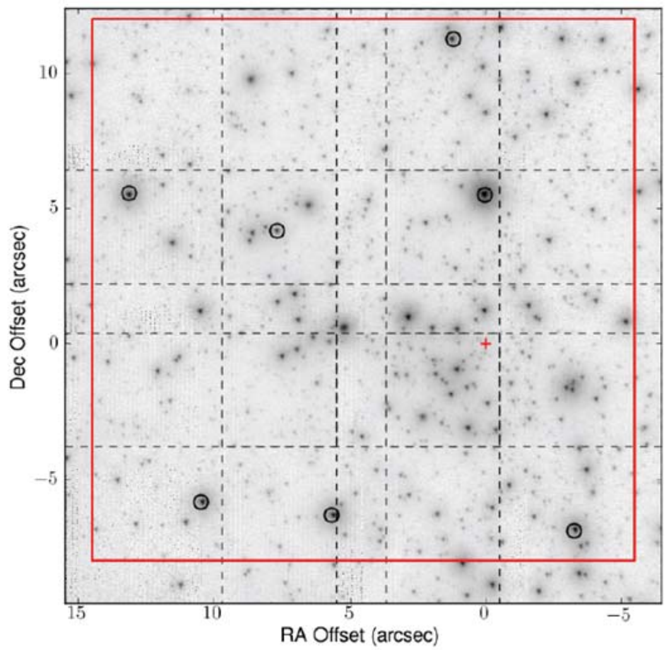


Figure 7: OSIRIS imager field of view (red outline)

One version of the new imager optical design is shown as a ray trace layout in Figure 8, inserted in the solid model of the OSIRIS optical bench and re-using the existing imager filter wheel. The design consists of a pair of off axis parabolic mirrors (OAPs) with additional flat mirrors for packaging. The first OAP is positioned at an off axis angle relative to the last OAP in the Keck I AO system that minimizes image distortion. The first OAP also creates a well formed pupil image for a cold stop and provides a collimated space for the imager filter wheels. The second OAP provides the focal reduction needed to achieve the required 10 mas imager pixel scale with the 18 µm pixels of the Hawaii-2RG. Although refinement will be needed, the layout indicates that the new imager will fit within the available space envelope in the instrument.

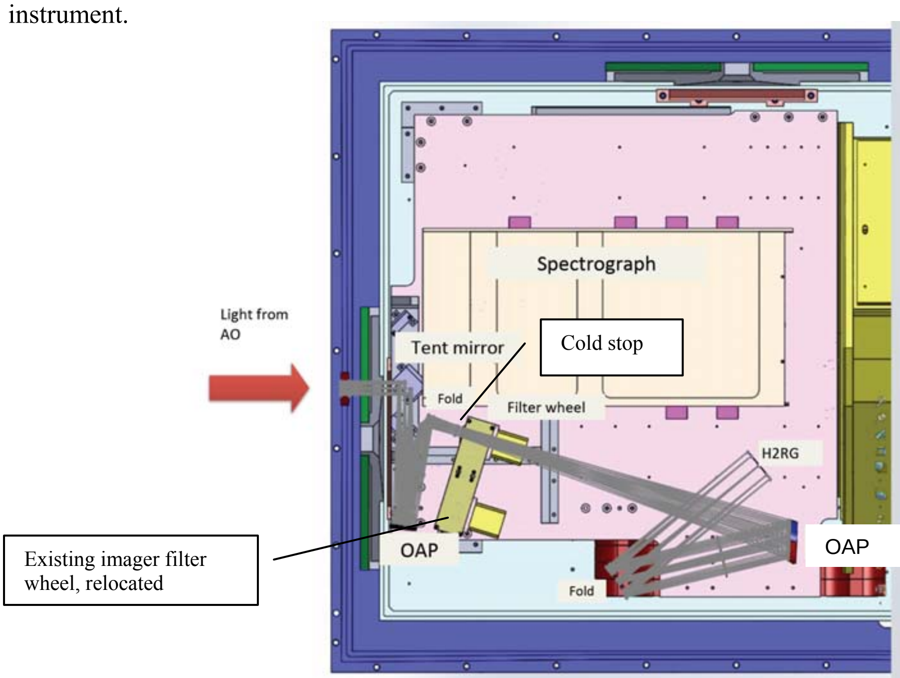


Figure 8: OSIRIS imager upgrade optical layout, plan view

A design review for the imager upgrade is planned for mid-2015, and the upgrade is expected to be ready for installation in mid-2016.

2.6 Telescope Control System Upgrade

The telescope control system (TCS) upgrade[16] is an internally led project to develop a replacement for the hardware and software used to point the Keck telescopes and track objects during observations using guiding commands from guide cameras or the AO system. Development of the upgrade began in 2010 and the project passed its detailed design review in late October 2012. The upgrade involves replacing mechanical, electrical and software components of the TCS. The overall goals of the upgrade are improved performance, increased reliability, reduced maintenance, and addressing serious obsolescence issues. Obsolescence is a major concern especially since a recent disaster recovery analysis at the Observatory found that obsolescence was the most significant factor affecting recovery from a disaster. Making an upgrade such as this also provides an opportunity for technology updates and an opportunity for knowledge diffusion and renewal.

The TCS provides drive and position/velocity sensing for the telescope azimuth and elevation axes, drive and position sensing for the telescope's secondary mirror for telescope focus and optical alignment, and the drive and position/velocity sensing for the telescope dome to keep the dome shutter opening aligned with the telescope aperture as the telescope is moved. The TCS also controls the Cassegrain instrument rotators and the facility rotators on the bent Cassegrain ports. The rotators on the Nasmyth platform instruments, including the telescope AO systems are controlled by the instruments and their motion is coordinated with TCS.

The TCS upgrade seeks to address performance limitations of the current TCS, particularly the open loop pointing and tracking performance and the maximum slew rate, both of which are currently below specification. The TCS upgrade does not seek to advance beyond the specification, but instead intends to actually deliver the original specified performance. Table 1 summarizes the key performance parameters for the TCS upgrade.

Parameter	Specification
Absolute pointing	1 " rms
Offset error (1° offset)	0.1" peak
Open loop tracking (10 min.)	0.1" rms
Slew rate (180° in azimuth, 90° in elevation)	120 s

Table 1: Key TCS upgrade performance goals

The design of the TCS upgrade uses as much of the existing TCS hardware and software as possible while eliminating obsolete components and replacing other selected components for improved performance, reliability and maintainability. Hardware being reused includes the azimuth and elevation drive amplifiers, motors, and tachometers, the azimuth and elevation brakes, hydraulics, limit and interlocks switches, manual control panels and e-stops. The existing rotation encoders, motors and drive amplifiers are also being reused. New hardware includes a number of 19-inch 2U rack controllers, Symmetricom PCIe timing boards, RocketPort serial extenders, Delta Tau Brick Controllers, National Instruments RIO and C Series IO, Heidenhain tape encoders and Rockwell PLCs with FLEX IO.

The TCS upgrade will replace the telescope's azimuth and elevation encoder systems, illustrated for the Keck II telescope in Figure 9. The elevation encoder system was prototyped in 2012, and this prototype provided valuable information regarding the design issues for this telescope axis. A second prototype was designed and implemented on Keck II in 2013. This version (shown at the top right in Figure 9) mounts the encoder tape on the drive track where the bar codes were located for the original elevation encoder system. The read heads (1 in service, 1 spare) are mounted on the existing elevation axis support structure. The azimuth encoder design (shown in the bottom right in Figure 9) mounts four read heads using a cylinder extended from the existing Coudé mirror structure located at the lower center of the telescope support structure. Bellows couplings connect the cylinder to the telescope and to a ring carrying the read heads. This ring is supported axially and radially by air bearings. A fixed tower surrounds the existing Coudé path at the center of the floor under the telescope and the encoder tape is mounted to a ring at the top of this tower. The new azimuth encoder assembly does not affect the usability of the Coudé path.

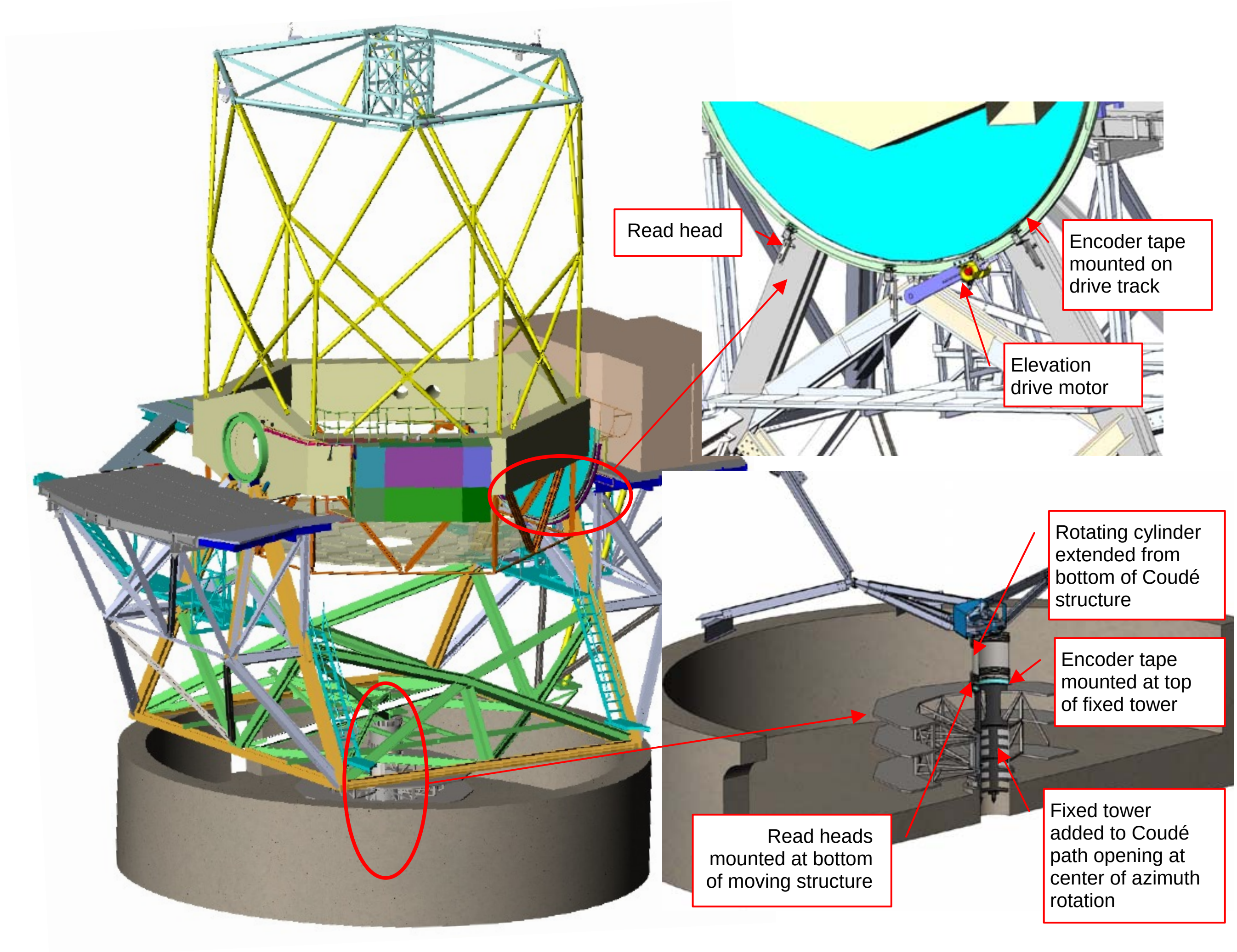


Figure 9: New azimuth and elevation encoders on the Keck II telescope
Note that the elevation encoder view (upper right) is from the opposite side of the telescope to that shown on the left side of the figure.

The TCS upgrade software runs on Red Hat Enterprise Linux with the Real Time patch. The software reuses all of the custom EPICS records (though some of the underlying algorithms are being updated), all top level database records, many subroutines, and the existing dome control software with the exception of device interfacing. All of the custom EPICS records have been ported, the CapFast schematics have been migrated to TDCT, the TCSpk pointing kernel has been integrated into EPICS, all of the new drivers have been tested, the timing subsystem and the configuration service have been implemented, and proof of concept demonstrations have been performed with the PLCs and motion controllers. Development is ongoing at the application level for each of the subsystems and includes SNL, DB configuration, C/C++ code, PLC and LVFPGA code.

Installation of the TCS upgrade on Keck II is underway. The upgraded Keck II dome control system has been tested, and the new control for the Keck II secondary is undergoing daytime testing. The installation of the Keck II azimuth encoder system is underway, and completion of the entire Keck II TCS upgrade is expected in early 2015. Installation on Keck I will follow in mid-2015.

3. CONCLUSIONS

Development of new instrumentation, upgrades to existing instrumentation, and renewal of our aging infrastructure are all part of the development activities at WMKO, and in this paper we have described our current activities in all three of these areas. We are constantly aware that our field does not stand still, but instead demands continual advances in capabilities and efficiency in support of advances in astronomical discovery. We are also aware that ground-based astronomy in the U.S. depends on very limited funding from public and private sources. Our development efforts must balance our desire for the newest and best with the realities of funding and the risks inherent in developing complex instrumentation. None of this would be possible without the efforts of many people including the development staff at WMKO and our partner institutions, and a number of companies in industry who provide materials, fabrications and services for our development projects. The development of new instrumentation is of course only part of the story at WMKO, and our overall success as a leading astronomical observatory results from the quality of science produced by our observing community, and the excellence achieved by our operations staff in supporting observing on both telescopes every night.

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